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Brown Dwarfs in the Pleiades Cluster: a CCD-based R, I survey ⋆

M.R. Zapatero Osorio, R. Rebolo, and E.L. Martín

Instituto de Astrofísica de Canarias, Vía Láctea s/n, E-38200 La Laguna, Tenerife, Spain

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Abstract. We have obtained deep CCD R and I mosaic imaging of 578 arcmin^2 within $1^\circ.5$ of the Pleiades' center – reaching a completeness magnitude $I = 19.5$ – with the aim of finding free-floating brown dwarfs. Teide 1, the best *bona fide* brown dwarf discovered so far in the cluster (Rebolo, Zapatero Osorio & Martín 1995), arose as a result of a combined photometric and astrometric study of ∼1/4 of our covered area. The extension of our two-colour survey provides eight new additional brown dwarf candidates whose photometry is rather similar to that of Teide 1. Several of them are even fainter. Follow up low-resolution spectroscopy (Martín, Rebolo & Zapatero Osorio 1996) shows that one of them is indeed a Pleiades brown dwarf. Most of the remaining candidates are background late-M dwarfs which are contaminating our survey, possibly due to a small (previously unknown) cloud towards the cluster which affects some of our CCD fields. We did not expect any foreground M8–M9 field dwarf in our surveyed volume and surprisingly we have found one, suggesting that its number could be larger than inferred from recent luminosity function studies in the solar neighbourhood.

Key words: Stars: pre-main sequence – Stars: late-type – Stars: low-mass, brown-dwarfs – Open clusters: Pleiades

1. Introduction

Photometric searches for free-floating, very low-mass stars and brown dwarfs (hereafter referred to as BDs) in young open clusters have been carried out during the last few years (see Jameson 1995 for a review). The Pleiades has become the favourite target due to its scarce reddening and relatively young age compared to other nearby clusters. Searches conducted in recently formed clusters take advantage of the fact that BDs are still young and bright, and hence, rather easy to detect. The expected brightness of all BDs becomes lower as they age. For instance, according to recent theoretical evolutionary tracks (Burrows et al. 1993; D'Antona & Mazzitelli 1994; Baraffe et al. 1995), a BD of 0.06 $M_\odot$ at the age of the Pleiades is ∼20 times more luminous than at the age of the Hyades. Furthermore, the Pleiades cluster presents another fortunate circumstance. It is well known that the borderline which separates stars from BDs takes place at 0.08–0.07 $M_\odot$ for solar metallicity. In the Pleiades cluster this particular mass range coincides with the preservation of Li (Magazzù, Martín & Rebolo 1993; Nelson, Rappaport & Chiang 1993; D'Antona & Mazzitelli 1994;) which provides a spectroscopic tool for discriminating BDs from stars (Rebolo, Martín & Magazzù 1992).

Li abundances in K-type, early and mid M-type stars of the Pleiades (García López, Rebolo & Martín 1994; Martín, Rebolo & Magazzù 1994; Marcy, Basri & Graham 1994) show that a large depletion has already occurred at the age of the cluster. However, one object named PPl 15 (M6.5) discovered by Stauffer, Hamilton & Probst (1994), presents a weak Li line suggesting that it has retained some of its initial content (Basri, Marcy & Graham 1996). The mass of PPl 15 should be around 0.08 $M_\odot$, which locates this object at the substellar limit in the Pleiades.Very recently, another object named Teide Pleiades 1 (hereafter, Teide 1)was found to have photometry, spectral type, radial velocity and proper motion that qualify it as a Pleiades member (Rebolo, Zapatero Osorio & Martín 1995). This object is less luminous, cooler and hasa higher Li abundance than PPl 15 (Rebolo et al. 1996), and therefore it is well located in the BD domain.

Teide 1 was discovered in the early stages of the R, I survey that we present in this paper. The survey has been extended to an area ∼4 times larger than the one covered at that time attaining similar limiting magnitudes. Eight new objects have been identified with R, I photometry very similar to that of Teide 1. In Sect. 2, we give a detailed description of the observations; Sections 3 and 4 present the photometric and proper motion measurements and a discussion of the results. Finally, conclusions are summarized in Sect. 5.

Send offprint requests to: M.R. Zapatero Osorio, e-mail: mosorio@iac.es

⋆Based on observations made with the Jacobus Kapteyn Telescope, operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias (IAC); on observations made with the IAC80 telescope operated by the IAC at its Observatorio del Teide; on observations made with the Nordic Optical Telescope in the Observatorio del Roque de los Muchachos; and on observations made with the 2.2 m telescope at the Spanish-German Astronomical Center, Calar Alto, Almería, Spain.

2. Observations

Our R, I photometric survey has been carried out using the following telescopes: the 0.8 m IAC80 at the Observatorio del Teide; the 1 m Jacobus Kapteyn Telescope (JKT) and the 2.5 m Nordic Optical Telescope (NOT), both at the Observatorio del Roque de los Muchachos, and the 2.2 m at Calar Alto Observatory. The CCDs used were a Thomson 1024×1024 (IAC80 and NOT) and a Tektronix 1024×1024 (JKT and Calar Alto 2.2 m), which provided fields of view of 54.5, 5.5, 31.5, and 22.5 arcmin^2, respectively. A total of ∼578 arcmin^2 (∼1% of the cluster total area) was surveyed in the R, I broad-band filters. Two exposures of typically 1800 s (IAC80, JKT) and 300 s (NOT and Calar Alto 2.2 m) were obtained in each filter in order to achieve similar limiting magnitudes in all four telescopes. Weather conditions during all the nights were always fairly photometric, while the seeing ranged between 0".6 and 2". In Table 1 we list the log of observations as well as the area surveyed by each telescope.

Table 1. Log of photometric observations

Telescope	Obs. date	Surv. area (arcmin^2)	$R_{\rm lim}$	$I_{\rm lim}$
IAC80	5–7 Jan 1994	125	22.0	21.0
NOT	7 Nov 1994	40	22.5	21.5
C.A. 2.2 m	26,27 Nov 1994	350	22.5	21.5
JKT	22,24 Nov 1995	63	22.5	21.5

We adopted the R, I broad-band filters because BDs were expected to be very red objects, $(R-I) \geq 2.0$, that should follow the sequence in the I versus $(R-I)$ diagram defined by the mid-M Pleiades stars (Hambly, Hawkins & Jameson 1993). On the other hand, current CCD detectors have a high efficiency at R wavelengths and, although it drops considerably in the I-band, this effect is compensated by the exceedingly intense brightness of BDs at these near-IR wavelengths.

We re-observed the fields of Jameson & Skillen (1989) using the IAC80; therefore, the BD candidates proposed by these authors are included in our survey. The goal was to derive proper motions by comparing the two epochs of observations separated in time by 7.17 yr. This is feasible because the cluster members have a large peculiar proper motion in comparison with field stars in the same region of the sky, and hence, proper motion measurements can be achieved within a few years. New fields observed with the NOT, JKT and Calar Alto 2.2 m telescopes were selected to be roughly 0°.5–1°.5 southeast far from the accepted center of the cluster. New photometric candidates were expected to arise from those images.

According to several recent reddening maps of the Pleiades (van Leeuwen 1983; Breger 1987; Stauffer & Hartmann 1987), only a fairly small portion of the cluster southwest of the cluster center suffers from high absorption. None of our fields fall within this region. Therefore, the expected reddening for our BD candidates is $A_I = 0.07$ mag and $E(R-I) = 0.03$ mag. In Fig. 1 the location of all the frames imaged during the four observing runs is presented to scale. Stars brighter than 6^{th} magnitude and M stars (Hambly et al. 1993) within 2°.5×2°.5 centered at $\sim 3^{\rm h}47^{\rm m}$, 24°7' (Eq. 2000) are also included for comparison. Although the region covered by our survey only represents a small fraction of the total area of the cluster, several interesting objects have been discovered (see the next sections).

Fig. 1. Location of our fields (open squares) within 2°.5×2°.5 of the Pleiades area. Central coordinates are $\sim 3^{\rm h}47^{\rm m}$, 24°7' (Eq. 2000). Filled circles stand for stars brighter than 6^{th} magnitude and for proper motion M members (Hambly et al. 1993) with I magnitudes in the range 13–17. The vertical gap in the M star distribution around $3^{\rm h}51^{\rm m}$ is due to the fact that there were no overlaps between the first and second epoch plates used by the authors, causing the lack of proper motion measurements for stars in that strip. The relative brightness is represented by circle diameters. North is up and East is left

3. Data analysis

3.1. Photometry

Raw frames were processed using standard techniques within the IRAF [1] environment, which included bias substraction, flat-fielding and correction for bad pixels by interpolation with values from the nearest-neighbour pixels. The photometric analysis was carried out using routines within DAOPHOT, which provides image profile information needed to discriminate between stars and galaxies. Instrumental magnitudes were corrected for atmospheric extinction and transformed into the R, I Cousins (1976) system using observations of standard stars from Landolt's (1992) list. Fields taken with the NOT and Calar Alto 2.2 m telescopes were overlapped by 0'.5 and 1'.5 respectively. On the basis of the photometry of stars that fall in overlapping regions of adjacent frames, we estimate the uncertainties to range from <0.05 mag at R, $I \sim 18.5$ to about 0.15 mag at 21.0 mag. Because no standard star beyond $(R-I) = 1.6$ was included in the transformation equations,

[1] IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

the uncertainties for the reddest, faintest objects are expected to be slightly larger.

Limiting magnitudes (listed in Table 1) for all the telescopes are quite alike as exposure times were scaled according to the telescope diameters. However, different seeing conditions caused the completeness magnitudes to differ not only from telescope to telescope but also from one exposure to another. NOT frames were always obtained in good seeing (<1") and therefore, go deeper than the IAC80, JKT and Calar Alto 2.2 m images. The comparison of the total number of stars per magnitude interval in each telescope to that observed with the NOT provides us with an accurate determination of the completeness of our survey. We estimate it to be R, I = 20.0, 19.0 (IAC80) and R, I = 20.5, 19.5 (JKT, NOT and Calar Alto 2.2 m). These results were confirmed by the comparison with predictions of the number of stars present in the Galaxy by Bahcall & Soneira (1981) and by Gilmore & Reid (1983).

Fig. 2. Colour-magnitude diagram for very low-mass stars and BDs in the Pleiades cluster. Dots stand for proper motion M Pleiads from Hambly et al. (1993); filled squares stand for the nine BD candidates of Jameson & Skillen (1989); open and filled circles stand for objects in our survey. The location of the substellar limit is indicated by PPl 15. The faintest BD in the cluster with proper motion measured, Teide 1, is also plotted

We present in Fig. 2 the I vs $(R - I)$ diagram for the Pleiades JKT, NOT and Calar Alto 2.2 m fields, combining data from Hambly et al. (1993) with the new observations. These authors published photographic magnitudes which were converted into the Cousins system using the transformation equations given in Bessell (1986). The straight line that separates Pleiads from field stars was derived by taking into account those previously known proper motion members. No reddening has been applied. To indicate the position of the stellar-substellar borderline in the Pleiades, we have included PPl 15 for which $R = 20.05 \pm 0.07$ was measured during the observing run carried out with the JKT. Its I magnitude was taken from Stauffer et al. (1994). Also shown in Fig. 2 is the BD Teide 1 (see next subsection). Because its substellar nature has been confirmed recently (Rebolo et al. 1996), objects found to present similar photometry to that of Teide 1 and located above the straight line might be BDs as well.

Table 2. Brown dwarf candidates in the Pleiades

Name	RA (J2000) ($^{\mathrm{h}\ \mathrm{m}\ \mathrm{s}}$)	DEC ($^{\circ}\ '\ ''$)	I	R–I
Calar Pleiades 1	3 51 04.0	23 51 02	18.18	2.93
Roque Pleiades 1	3 50 00.0	23 34 03	18.43	2.50
Calar Pleiades 2	3 51 15.0	23 54 01	18.66	2.50
Calar Pleiades 3	3 51 26.0	23 45 20	18.73	2.54:
Teide Pleiades 1*	3 47 18.0	24 22 31	18.80	2.74
Calar Pleiades 4	3 50 43.0	23 52 46	18.88	2.37
Calar Pleiades 5	3 50 52.1	23 51 48	19.01	2.33
Calar Pleiades 6	3 51 21.0	23 52 10	19.20	2.59:
Calar Pleiades 7	3 51 21.3	23 52 10	19.7:	2.52::

Notes.
* Teide Pleiades 1 is a proper motion member.
For uncertainties in photometry and coordinates, see text. Colours labelled with a colon have uncertainties of ±0.20 mag; the one labelled with two colons, ±0.35 mag.

Table 2 provides the names, magnitudes, colours and positions for the new proposed Pleiades BD candidates. They are named according to the observatory in which they were first detected followed by the word *Pleiades*, and numbered according to their increasing I-band apparent magnitude. Hereafter, we will use an abridged version of the names which omits the term *Pleiades*. Coordinates are accurate to approximately ±2".5. Finding charts (2'×2' in extent, I-band) are provided in Fig. 3.

3.2. Proper motion survey

Approximately 25% of the total area covered in our survey was chosen to overlap regions previously observed by Jameson & Skillen (1989). We were looking for BD candidates whose photometry and proper motion support membership in the Pleiades cluster. For proper motion measurements we have mainly used I-band frames because the objects which interest us are brighter in this filter than in R and, therefore, their centroids can be determined more accurately. The astrometric procedures for deriving proper motions were those described by Hawkins (1986) and have been used successfully by Hambly et al. (1993, 1995). We estimate that our survey is complete in the range $16.5 < I < 19$ mag.

After having covered 125 arcmin^2 around the center of the cluster, a sole object arose with photometric and proper motion determinations perfectly compatible within the error bars with those that identify the cluster. It was only detected in the I-band ($I = 18.80 \pm 0.07$) suggesting that its colour should

Fig. 3. Finding charts (2'×2' in extent, I-band) for the BD candidates listed in Table 2 and Teide 1. North is up and East is left

be very red [$(R–I) > 2.2$]. We named it as Teide 1 (Rebolo et al. 1995). The field in which Teide 1 appeared was re-observed again during the NOT campaign (8 years after Jameson & Skillen's run), yielding $(R–I) = 2.74\pm0.10$ mag. The R, I photometry and coordinates for Teide 1 are listed in Table 2. From November 1986 to November 1994, the measured proper motion of Teide 1 was $\mu_{\alpha\cos\delta} = 0.13"\pm0.07"$ and $\mu_\delta = -0.28"\pm0.13"$, which is consistent within the error bars with that of the Pleiades cluster for the same time interval (that is $\mu_{\alpha\cos\delta} = 0.20"\pm0.05"$ and $\mu_\delta = -0.36"\pm0.05"$, Jones 1981). Teide 1 has been studied spectroscopically by Rebolo et al. (1995), Rebolo et al. (1996) and Martín, Rebolo & Zapatero Osorio (1996). They conclude that the measured proper motion and radial velocity, the Hα emission, the M8–M9 spectral type, the R, I photometry as well as the fact that it has preserved a large amount of Li in its atmosphere, are all consistent with Teide 1 being a Pleiades BD.

The nine CCD survey objects of Jameson & Skillen (1989) were present in our proper motion analysis. Bearing in mind that PPl 15 fixes the frontier of the very low-mass stars in the cluster, only JS1 (= PPl 3, Stauffer et al. 1989) and JS2 might be BD candidates according to their I magnitude. Our photometric analysis for JS1–9 yielded within the error bars similar magnitudes and colours than those previously published. Nevertheless, they (except JS9) lie about 0.5–1 mag below the straight line in Fig. 2 (i.e. 1.5–2 mag below the Pleiades sequence), suggesting that these objects are probable non-members according to their R, I photometry. From previous works, it is known that JS4, 6, 8 and 9 failed as proper motion members (Hambly et al. 1991). JS1, 2, 3, 5 and 7 were either too faint or blended to be included in their study and they were hence rejected. JS1 is unlikely to be a member due to its IR photometry (Stauffer et al. 1989; Hambly et al. 1991). Stringfellow (1991) argues that none of them are members on the basis of their location on the theoretical HR diagram. Our proper motion study does not provide support for their membership regardless of their photometry.

4. Discussion

With R, I photometric data only we cannot conclude that our BD candidates listed in Table 2 are true Pleiads. We will discuss briefly what kind of objects are expected to be contaminating a survey like ours and will try to quantify each of them as follows.

Distant galaxies may be one source of contamination. However, we feel confident that our new BD candidates are stellar-like objects because most galaxies with I magnitudes around $I = 18$–19 might be resolved in our survey given the pixel size of the detectors and seeing conditions. Therefore, they would not have fitted the point spread function, and our BD candidates certainly did. The recent I, K survey by Jameson et al. (1996) has shown that the primary contaminants are faint, red galaxies. It seems that the use of optical and near-IR filters allow to better discriminate BDs from these presumably distant galaxies, despite the fact that BDs are much fainter at these wavelengths than at K-band.

Another source of contamination comes from background late-M giants. We can estimate this kind of contribution given the recent study of the luminosity function for free-floating M stars at the end of the main sequence by Kirkpatrick et al. (1994). From their survey (limiting magnitude $R = 19$), the authors argue that these objects are only relatively numerous in areas within 10° of the Galactic plane. As the Pleiades cluster is located well away from this region (at $b = -24°$), the expected number of background late-M giants in our survey is negligible.

Due to their location in the I vs $(R-I)$ diagram, our BD candidates could be Pleiades substellar objects, or old field M7.5–M9 dwarfs just superimposed on the cluster or else background, reddened field M5–M7 dwarfs. We have used the luminosity function for main sequence stars in the solar neighbourhood of Kroupa (1995) in order to estimate the number of M5–M7 dwarfs that could be present in the volume that our survey has covered. For star counts out of the plane of the Galaxy the space density is well represented by an exponential law. Adopting the scale height for dwarf M stars given by Mihalas & Binney (1981), a total of seven stars may be contaminating, one of which could be a foreground star. Furthermore, M5–M7 dwarfs were found to be rather abundant in Kirkpatrick et al.'s (1994) work: 33 dwarfs out of 95 turned out to have spectral types within this range (i.e. 35%). On the contrary, only one M8–M9 star was discovered, suggesting that the local density for this spectral range is $\sim$0.0024 pc^{-3}. Because our survey in the JKT, NOT and Calar Alto 2.2 m covered a volume about 10 times smaller, the probability of finding such late spectral type objects along the line of sight towards the cluster is almost negligible. We have obtained similar results using the luminosity functions of different authors (Leggett & Hawkins 1988; Tinney 1993). Therefore, based on these statistics the main source of contaminating objects in our survey comes from M5–M7 dwarfs.

Martín et al. (1996) have conducted low-resolution spectroscopic observations of all our BD candidates. The likelihood of membership was assessed via the study of their spectroscopic properties compared to some very late field M stars and Teide 1. As expected from previous estimates, all the BD candidates are late-M dwarfs. However, only Calar 3 turns out to be an object very similar to Teide 1 and therefore, a very likely Pleiades BD. Based on the available data this object clearly meets all the membership criteria. The Hα emission, radial velocity, spectral type and photometry are consistent with Calar 3 being a member of the cluster. This result yields a success rate of two genuine BDs out of our nine candidates ($\sim$22.5%). If an uniform distribution within the cluster is assumed, the expected number of Pleiades BDs with $I = 18.5$–19.0 would be about 200 objects, suggesting that the probable total number of BDs in the substellar domain is rather large. The implications of this result for the mass function are beyond the scope of this paper and will be addressed in a future work which takes into account not only our survey, but all the surveys carried out so far in the cluster.

Other very interesting objects have arisen as by-products of our survey. Calar 1 and Roque 1 are surprisingly high radial velocity, very late-M dwarfs and hence, probably non-members that need further observations in order to understand their nature. To our knowledge, Calar 1 (M9) and Roque 1 (M7) have the highest radial velocity ever measured among the latest dwarfs. According to their spectral types and I apparent magnitudes, Calar 1 and Roque 1 should be located at approximately 45 pc and 111 pc respectively, i.e. foreground objects. The existence of an M7 dwarf at this distance in our survey was somehow expected based on previous surveys, whereas the discovery of an M9 dwarf remarkably disagrees with expectations.

Its detection could be indicative of a large, yet undiscovered, population of field M9 dwarfs in the solar neighbourhood.

Calar 2, 4, 5, 6 and 7 are likely M4–M6.5 background, reddened dwarfs rather than members of the cluster. These stars are the main source of contamination in our colour-magnitude diagram. All of them lie within a quite small region of the sky ($\sim$20 arcmin^2) as shown in Fig. 4, suggesting that this area may suffer from enhanced reddening. We have estimated the mean colour excess, $E(R-I)$, in this little region by comparison of the observed $(R-I)$ colour with the reddening-free colour for each spectral type given by Kirkpatrick & McCarthy (1994). Calar 7 was excluded from the calculations due to the large uncertainty in its photometry. The mean reddening is determined to be $E(R-I) = 0.30\pm0.09$ mag, possibly indicating the existence of a cloud towards the Pleiades at $\alpha = 3^{\rm h}51^{\rm m}$, $\delta = 23^\circ 53'$ (Eq. 2000). Whether this cloud is either foreground, or background or within the cluster still remains unknown. We note that the BD Calar 3, located at $\sim$9' distance, is unlikely to be affected by such a high reddening since its spectra and photometry are extremely similar to those of Teide 1.

Fig. 4. Spatial distribution of our Calar BD candidates (filled dots) and the fields observed with the 2.2 m Calar Alto telescope (scaled open squares). Central coordinates are those of Calar 1 (the plot scale is 25"/mm). North is up and East is left

According to the degree of contamination by field M dwarfs found in our survey, we conclude that determinations of the initial mass function based on candidates whose membership relies only on two-colour photometry are likely to significantly overestimate the number of very low-mass members in the cluster. Further analysis is needed in order to determine membership and consequently derive reliable mass functions. In Martín et al. (1996) we have proved that a R, I photometric survey followed up by low-resolution spectroscopy constitutes a reliable tool to assess membership to the cluster. Moreover, we will also explore the potential of IR photometry to characterize Pleiades BDs (Zapatero Osorio, Rebolo & Martín 1996).

Calar 3 and Teide 1 are young BDs in the Pleiades cluster with quite a high level of confidence. The general shape of their optical and near-IR spectra is very similar to that of field M8–M9 dwarfs (see Rebolo et al. 1995; Martín et al. 1996). However, we have found that the $(R-I)$ colour of Calar 3 and Teide 1 is 0.2–0.4 mag redder than those of field dwarfs with the same spectral type. A more depressed pseudocontinuum at the R-band (fainter R's) is observed in the low-resolution spectra of Calar 3 and Teide 1, suggesting that the colour offset is real. We have computed the $(R-I)$ differences between Calar 3, Teide 1 and vB10, LP412–31 LHS2065 using the published spectra (Rebolo et al. 1995; Martín et al. 1996) and found them to be in good agreement with the measured photometric differences within the uncertainty bars. This suggests that although systematic errors in the photometry could exist since our BDs are much redder than the reddest standard star used for the calibrations, they should be small. Possible explanations that could account for the colour offset may be based on the lower gravity in the Pleiades' members than in old dwarfs, and on its relationship with the dust formation in the atmospheres of these very cool objects (Tsuji, Ohnaka & Aoki 1996).

5. Conclusions

We have conducted R, I observations of 578 arcmin^2 in the Pleiades ($\sim$1% of the cluster area) reaching completeness magnitudes R, $I = 20.5$, 19.5 mag and limiting magnitudes $\sim$1 mag fainter. As a result of a combined photometric and proper motion survey covering 125 arcmin^2 around the cluster's center (i.e. $\sim$1/4 of the total surveyed area), we found Teide 1 (Rebolo et al. 1995), whose substellar nature has been confirmed recently by the Li test (Rebolo et al. 1996). The extension of our two-colour survey yielded eight new BD candidates which lie along the substellar sequence of the Pleiades and whose R, I photometry is rather similar to that of Teide 1.

Further spectroscopic studies (Martín et al. 1996) of our BD candidates reveal that $\sim$25% are true BDs (Teide 1 and Calar 3) showing that our technique is successful in finding substellar objects. The remaining Calar objects and Roque 1 are likely to be late-M field dwarfs. Particularly, the fact that a field M9 dwarf (Calar 1) was found in our survey may be indicative of a large, yet undiscovered, population of these very late and cool objects in the solar neighbourhood. We have found that Calar 3 and Teide 1 (spectral type M8), the two genuine BDs in the Pleiades, are redder in the $(R-I)$ colour than field stars of the same spectral type in the sense that they have fainter R-magnitudes. We argue that this feature could be an effect of the lower gravity of Pleiades BDs because of the youth of these objects.

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